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Market Impacts of Rare Earth Element Use in Solid Oxide Fuel Cells

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Report Number: R102 06 01F2

Date: October 18, 2010

Prepared for: National Energy Technology Laboratory, In Sub-Contract to Leonardo Technologies, Inc.

Contract Number: DE-FE0004002 (Subcontract: S013-JTH-PPM4002 MOD 00)

Summary

Rare earth elements (REEs) are critical to the function and performance of solid oxide fuel cells (SOFCs)[1]. Given the concentration of commercially minable REE deposits and production in China (and especially given recent tightening of its export quota), the US Department of Energy is interested in understanding how REE demand for SOFC applications could impact REE markets and *vice versa.*

Yttria (yttrium oxide), lanthanum oxide, and ceria (cerium oxide) are important materials in the ceramic cells that form the core of any solid oxide fuel cell, imparting on the functional layers of the cells ionic conductivity, electronic conductivity, and/or structural strength. Gadolinium, scandium, and samarium are also used in some SOFC designs.

The amounts of REEs contained in state-of-the-art SOFC are modest, and represent less than 5% of annual production (Table 1). Spent SOFC stacks and production waste will likely be recycled for their metal and REE content, which would reduce REE demand for stack replacements by 80-90%.

Table 1 Overview of SOFC-Driven REE Demand, REE Production and Reserves

	REE Content of SOFC	SOFC-Driven Net REE Demand[2]	REE Production (2009)	Estimated Reserves
	g/kW	t/yr (2030)	t/yr	T
Yttria	21	40	9,000	540,000
Lanthanum Oxide	9.2	95	>12,000	>10 million
Other REE (Ce, Gd, Sm)	<3	<12	20,000	~50 million

Market prices for these REEs have risen considerably over the past year, first doubling and then spiking to 4-5x their 2008 price levels in the past few months. At today's prices then, REEs would contribute about $12/kW to the first cost of SOFC systems (based on pre-2008 prices bulk REE cost would have been about $1/kW). While noticeable, this is a small fraction of overall

[1] In the production of SOFC, REEs may be used as metals, oxides, or salts. However, for consistency and to avoid confusion, they will be expressed as elements throughout this paper.

[2] Assuming annual SOFC production of 4 GW/yr of new capacity plus 4 GW/yr of stack replacements assuming 90% REE recycling.

SOFC manufactured cost, representing less than 10% of the SOFC stack, about 2% of the SOFC module in powerplants, and less than 1% of the SOFC powerplant cost. The combined impact of first cost and stack replacement would contribute about $0.50/MWh to the levelized cost of electricity (LCOE) of SOFC powerplants. This is well within the margin of error of the overall LCOE estimate (around $80/MWh).

In summary, REE demand for SOFC applications is not likely to substantially impact overall supply – demand balances for REEs. And while recent price increases clearly affect the production and O&M cost for SOFC systems, plausible fluctuations in REE prices are not likely to fundamentally alter the economic viability of SOFC in power generation applications.

Introduction & Background

The US Department of Energy (DOE) has recognized that several emerging energy technologies rely to varying degrees on the unique properties of rare earth oxides (REEs)[3]. In fact, the DOE recently requested information from industry regarding the potential impact of emerging energy technologies on REO markets (DOE 2010).

The US DOE (the Office of Fossil Energy through the National Energy Technology Laboratory, primarily) has supported Solid Oxide Fuel Cell (SOFC) development for years, most recently through its Solid State Energy Conversion Alliance progam(Surdoval, Singhal et al. 2000; Vora 2010). Partly due to this support, SOFC technology now appears to be nearly ready for commercialization, with some companies now projecting initial commercial products to be available over the next five years (Delphi 2009; Lim 2010). SOFC rely on unique properties of several REEs, especially in their core components: the ceramic cells. These multi-layer ceramic cells contain several REEs or REE-based components. Almost all SOFC designs contain yttrium (yttrium oxide, yttria, is used as a stabilizer in zirconia in electrolyte, anode, and often cathode) and lanthanum (as the key component of the cathode) and in some cases cerium, scandium, gadolinium or samarium[4]. Therefore the DOE's NETL thought it relevant to investigate the potential impact of SOFC commercialization on REE markets and *vice versa*, and hence the DOE requested the preparation of this paper. This paper is organized in the following categories:

1. ***Uses of REEs in SOFC:*** which REEs are used in SOFC, how, and what is their function? What substitutes are available?
2. ***Impact of SOFC on REE Demand:*** how will commercialization of SOFC increase demand in REEs and how might recycling of REEs used in SOFC impact demand?
3. ***Impact of REE Cost & Availability on SOFC Commercialization:*** how would changes in availability and price of REEs affect the economic viability of SOFC and its commercialization

[3] The rare earth elements are: yttrium, scandium, and the lanthanides (atomic numbers 57 – 71, including lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium). Note that strontium is not considered an REE.

[4] In SOFC REEs are typically found as oxides (rare earth oxides or REOs), but for consistency and transparency, we will refer to the elements throughout this paper.

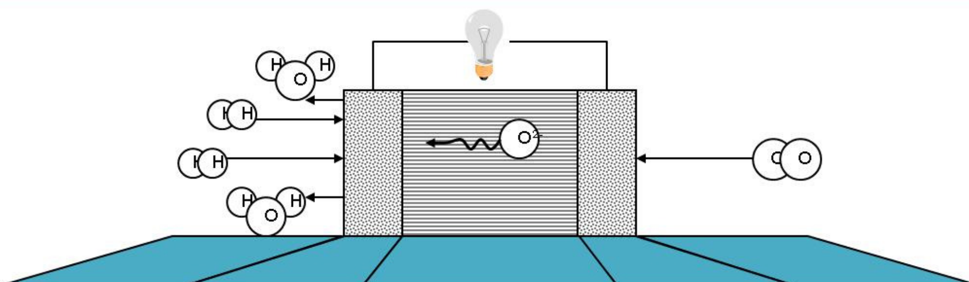
Uses of REEs in SOFC (DOE RFI[5] Category 2)

REEs in the SOFC Ceramic Cells

REEs fulfill crucial roles in the core electrochemically-active components of SOFC: the ceramic cell.

Basic SOFC Function and Materials

The heart of any SOFC is a multilayer ceramic cell, which allows the generation of power by electrochemically oxidizing the fuel. A simple overview of the ceramic cell's function and architecture are shown in Figure 1.



	Fuel Supply	Anode	Electrolyte	Cathode	Oxygen Supply
Function	• Fuel (H_2, methane, syngas, hydrocarbons) • Transported and distributed to anode	• Catalyzes electrochemical oxidation of H_2, Other fuels • Collects electron current	• Provides for ion transport (Oxygen ions moving from cathode to anode) • Prevents transport of electrons or molecules (E.g. molecular gases)	• Catalyzes electrochemical Reduction of O_2 • Distributes electron current	• Oxidant (air) • Transported and distributed to cathode
Thickness (µm)[1]		100 - 1000	5 - 100	50 - 1200	
Material[2]		Nickel – YSZ cermet	YSZ, LSGM, or ScSZ	LSM, LSC, LSCF, often composite with YSZ[3]	

1. The thickness depends strongly on cell architecture and manufacturing method. In many designs, one of these layers provides mechanical strength / support during manufacturing (anode-, electrolyte-, and cathode-supported cells), which requires such layers to be thicker. In a few designs, another ceramic layer provides the support.
2. YSZ – Yttria-stabilized Zirconia, containing typically 8% Yttria; ScSZ–Scandia-Stabilized Zirconia; LSGM – Lanthanum Strontiom Gallate Magnesite; LSM – Lanthanum Strontium-Manganate; LSF – Lanthanum – Strontium – Cobaltite; and LSCF – Lanthanum Strontium Cobalt Ferrite
3. Sometimes interlayers are used between the electrolyte and cathode. E.g. GDC (gadolinia-doped ceria) and SDC (samaria-doped ceria) are used as barrier layers in this function

Figure 1 Overview of Architecture, Function, and Materials of SOFC

As can be seen from the diagram, the ceramic cells contain several ceramic oxides with REEs:

- Yttrium is used as a dopant to stabilize the zirconia commonly used for the electrolyte, and sometimes in the electrodes as well. Yttria stabilizes the particular crystal structure that provides the ionic conductivity for the electrolyte (and electrodes)[6]. The yttria

[5] Categories from DOE's RFI (Request for information)

[6] i.e. the yttria stabilizes the crystal structures that provide oxygen mobility (and hence ionic conductivity) combined with low electrical conductivity.

doping level is most typically 8 mole % in those structures (or about 14% yttria or 11% yttrium by weight) but different doping levels are sometimes used, especially for structural components (e.g. the anode support in anode-supported cells). The most commonly considered alternatives to YSZ as an electrolyte are Scandia-Stabilized Zirconia (ScSZ) and Lanthanum Strontium Gallate Magnesite (LSGM), each of which contain significant fractions of scandium or lanthanum, each of which are also REEs. Aside from its role as electrolyte, YSZ is often used in SOFC electrodes (anode, cathode) to provide some ionic conductivity to electrode materials that don't have enough, and, in some SOFC, as a structural cell support. For example, a Ni-YSZ cermet is commonly used as anode material in SOFC. Similarly LSM (see below) cathodes are often mixed with YSZ.

- Lanthanum is another common and key component of most SOFC: several of its oxides provide the electronic conductivity and with high catalytic activity for oxygen reduction needed for efficient cathodes and some, in addition, combine ionic and electronic conductivity[7]. Common compositions are shown in Table 2. The table suggests that while a variety of cathode materials is being considered, many contain ~50% lanthanum. The literature reports experience with several REE-free cathode materials (Singhal and Kendall 2003) though not all alternatives necessarily lead to lower cost cathodes even at today's REE prices (e.g. platinum was used in early SOFC experiments).
- Doped ceria (usually doped with samarium, SDC, or gadolinium, GDC; samarium and gadolinium are also REEs) is commonly used in interlayers used between various SOFC ceramic cell layers (especially in the cathode-electrolyte interface) to prevent or minimize unwanted reactions between electrochemically mismatched layers. Although it may be possible to substitute the REEs in the interlayer structures, the amounts used are so small that this is likely not to be a priority in the near future.

[7] LSM has been commonly used as a SOFC cathode. It is commonly mixed with YSZ to provide the cathode with mixed ionic electronic conductivity (MIEC). More recently, LSC, LSF, and LSCF, which are MIEC cathode materials, have gained in popularity (Borglum (2005), Shaffer (2004)).

Common Name	Chemical Formula	La Content[8]	Other REO Content[3]	Comments
YSZ	Y_2O_3/ZrO_2	-	Y (3-8%)	
LSM	$La_xSr_yMnO_3$ (x= 0.8 – 0.85; y = 0.15 – 0.2)	56%	Sr (9%)	Commonly mixed with YSZ
LSCF	$La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$	44%		
LSC	$La_{0.6}Sr_{0.4}Co_{0.4}O_3$	51%		
LSF	$La_{0.6}Sr_{0.4}FeO_{3-\delta}$	44%		
SDC	$Ce_{0.8}\ Sm_{0.2}O_{1.9}$		Ce (80%) Sm (20%)	
GDC	$Ce_{0.8}\ Gd_{0.2}O_{1.9}$		Ce (80%) Gd (20%)	

Table 2 Overview of REO Contents of Various SOFC Materials

SOFC Materials Use in Ceramic Cells

As shown above, all SOFC ceramic cells currently contain some REEs. However, the amounts used (in terms of unit weight per unit power output, e.g. g/kW) are heavily dependent on the cell materials used, cell architecture, and cell power density, as is shown in Figure 2 below.

The overall REE content of planar anode-supported SOFC is modest: around 30 g/kW or less. Tubular cathode-supported SOFC contain ~1500 g/kW[9]. For perspective, the figure for planar anode-supported SOFC is about 100x the platinum loading targets DOE has for polymer electrolyte membrane(aka proton exchange membrane, PEM) fuel cells for vehicle applications (which are 0.2 g/kW for 2015). Platinum (and other Platinum Group Metals or PGMs) are about 10,000 times less abundant than REEs. Even at today's REE prices (September 2010) PGMs are ~500 – 1000 times more expensive than REEs.

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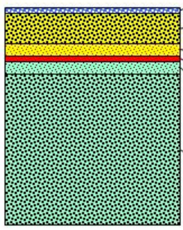
[8] For consistency, REEs are expressed in this paper as their elements, rather than as their stable oxides, i.e. Y_2O_3, La_2O_3 etc.

[9] The tubular cells discussed here are flattened, high-surface area tubes, not the older type cylindrical tubes. Other SOFC architectures, including those based on planar electrolyte-supported and tubular anode-supported cells, will contain different amounts of each of the REEs, falling between the two cases discussed here. SOFC that are supported on a REE-free substrate (e.g. strip design cells) may have significantly lower REE content than planar anode-supported cells.



	Planar Anode-Supported	Tubular Cathode Supported
Layer Thickness (µm)		
Cathode Contact Layer	LSC 10	NA
Cathode Current Collector/Support	LSCF 30	LSM 1200
Cathode Interlayer	GDC / SmDC 5	NA
Electrolyte	YSZ 8	YSZ 20
Anode Active Layer	Ni-YSZ 25	Ni-YSZ 100
Anode Support	Ni-YSZ 600	NA
Typical Cell Performance (W/cm^2)		
Cell-Performance[2]	0.4 (0.3 – 0.6)	0.2 (0.15 – 0.3)
Typical REO Content (mg/cm^2, g/kW, measured as metals)		
Lanthanum	4, 9.5	200, 1400
Yttrium	10, 21	2.9, 19
Cerium	1, 2	-
Gadolinium/ Samarium	<0.3, <0.6	-

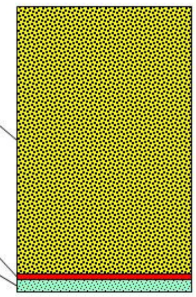


Figure 2 Materials and REO Content of Some Typical SOFC Structures Reflecting the Current State-of-the-Art (for detailed Assumptions, see (Thijssen 2007))

As can be seen in Figure 3, the REE content of SOFC is strongly influenced by the cell structure. Anode-supported SOFC have dramatically (~40x) lower overall REE content than tubular cathode-supported cells, mainly because:

- The supporting anode of planar anode-supported cells has a 10x lower REE content (~5% Yttria, compared with ~50% lanthanum in tubular cells) ,
- The supporting layer (the thickest layer) is less thick (~600 µm for planar anode-supported cells vs 1200 µm for tubular cells),
- Tubular cells tend to have more inactive area than now common large-format planar cells.

In addition, there is a significant difference in the types of REOs used in each type of SOFC (see Figure 3):

- REO content in tubular cathode-supported SOFC is dominated by lanthanum use. This is the consequence of the thick structural cathode made of LSM (Which is ~50% lanthanum)

- Lanthanum and yttrium dominate REO content of planar anode-supported SOFC, together responsible for about 75% of REO content. Cerium and gadolinium or samarium represent the balance.

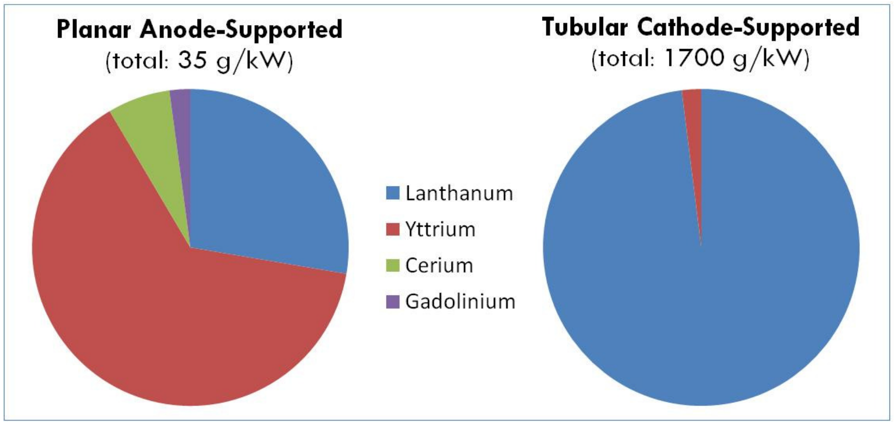


Figure 3 REO Content of Typical State-of-the-Art Planar Anode-Supported and Tubular Cathode-Supported SOFC[10]

The production processes currently envisioned for most planar SOFC mainly involve tape casting, calendaring, and screen printing[11](Thijssen 2007). At maturity, the process yields associated with such processes are typically around 90- 95%. Several studies confirm that such figures are plausible for SOFC and are indeed consistent with pilot production experience.

When considering all of the uncertainties in cell material use, architecture, and production methods the REE use in the production of SOFC ceramic cells based on current state-of-the-art technology already shows a fairly broad range (Figure 4):

- Layer thicknesses between designs vary by a factor two. The supporting layers for planar anode-supported designs vary between about 600 – 800 μm.
- Material choices for at least some of the components could affect uses, especially of the minor constituents (such as cerium, gadolinium, and samarium), which may or may not be used depending on the cell architecture.
- The manufacturing process overall may be expected to reach around 90-95% yield, which has been demonstrated by some developers using pilot production

[10] Cell structures and material uses are consistent with the current state-of-the-art. Details on cell structure are discussed in detail in Thijssen (2007) ,current performance was based on Vora (2010), Ghezel-Ayagh (2010), and Pierre (2010). Figures are on mass basis, accounting for REEs as elements

[11] Other production processes considered, such as extrusion and plasma spray methods may have lower yields, but the losses can be relatively easily recycled either inside the process, or back to the raw material suppliers. As a consequence, the net REO demand from these processes is dominated by the REO content of the product, with process losses a relatively modest factor.

equipment(Borglum 2005). However, yield on individual layers may be lower (e.g. because of overspray in plasma spray processes).

- Variations in power density further broaden the range. In this analysis, power densities for planar anode-supported cells between 0.4 – 0.5 W/cm^2 have been taken into account, consistent with recent performance

In the future, reductions in REE content of SOFC can be expected, especially if REE prices remain high (see Figure 4 again). This trend is likely because of three principal factors:

- *Increases in power density* will reduce REE content per kW, even if the REE use per unit active area stays the same
- *Reduction of layer thicknesses* especially of the support layers can drastically reduce REEs content
- *Changes in layer composition* can reduce REE content (e.g. via substitution by other materials).

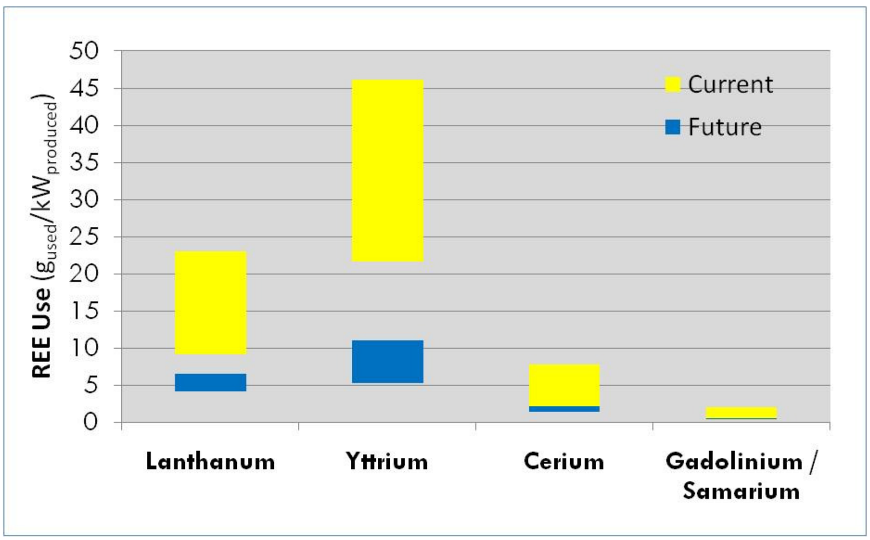


Figure 4 REO Use for the Production of Planar Anode-Supported SOFC Including Production Losses. Ranges Reflect both Typical Current State-of-the-Art and Potential for Future Improvements by 2015[12]

The REEs used in current processes and contemplated for production of SOFCs are high-purity fine powders of the respective REOs (i.e. oxides, they are used in tape casting, screen printing, and plasma spray processes primarily). Currently, purity requirements for these applications are typically in the 99.5% or better range. The purity requirements can, in some cases also be more prescriptive in terms of the specific impurities of interest (e.g. Si). The purity requirements

[12] Range for current state-of-the-art reflects a range of power densities, layer thicknesses, and compositions. Future projections consider improvements in power density, layer thickness, and some material substitution.

vary somewhat according to the precise materials system and cell architecture used. In research projects, higher purities are sometimes used out of an abundance of caution to minimize experimental variations (the added cost of high purity is small compared to the overall cost of the tests).

In addition to the purity requirements, the particle size distribution and surface area of the powders are of importance and differ according to the use of the powder. For example, for the electrolyte typically a fine powder is needed to facilitate rapid densification while for electrodes surface area is typically important.

The price impact of specifications is considerable: ultra-fine pure powders typically sell for 3-10 times the bulk material (still 99.9% pure) market price. The large mark-up results from the additional processing cost, and the supply-demand dynamics in markets for these pure products. Ergo, when basic REE prices increase, the increase in high-quality REO powders may be expected to be less than proportional. In addition, while most REE production is concentrated in China, the purification and processing of REOs is (still) partly the domain of Japanese and Western specialty ceramics companies. Nevertheless, to be conservative, we assumed that the mark-up factor between bulk REE prices (FOB China) and fine powder prices remains constant.

Other REE Uses in SOFC Systems

While use in ceramic cells is clearly the highest-impact use of REEs in SOFC, we want to mention other potential uses for completeness. Other applications of REEs in SOFC systems could include:

- Reformer / fuel processing catalysts may contain certain REEs as catalytic agents or support. Some developers have considered the use of ceria-based catalysts for reforming hydrocarbon fuels.
- Some SOFC systems call for an exhaust gas catalytic oxidation device, which may use a ceria-based catalyst.

Nevertheless, use of REEs in these applications is far from universal, and in most applications competitive alternative materials are available. Even where REEs are used outside the stack, the amount of REEs used in is less than 10% of that used in the ceramic cells. Therefore, we will not delve any more deeply into these other uses of REEs for SOFC systems at this point.

Impact of Stack Replacement

Because current SOFC stacks require periodic replacement (because of gradual irreversible degradation in performance) we must consider the REE demand resulting from the demand for replacement stacks (in addition to stacks for new systems). Currently SOFC stacks degrade at a rate of around 1% per 1,000 hrs (Borglum 2009; Kerr 2009), which would result in a service life of 2 yrs or less. However, in order to be commercially viable stack life should be extended to about 5 yrs, and the DOE has set R&D targets commensurately. As technology improvements proceed, stack life is expected to continue to improve after the initial commercialization of SOFC. Although technically different, Phosphoric Acid Fuel Cell (PAFC) stack life was around 20,000 hrs for the initial commercial systems, while current stacks last for over 60,000 hrs (UTC-Power 2005). Similar improvements were made with the molten carbonate fuel cells (which are more like SOFC). So for our projection, we consider an initial stack life of around 5 yrs (in 2015) and an improvement to a 10 yr stack life by 2030.

Impact on Demand for REE from SOFC, Impact of Recycling (USDOE RFI Categories 3, 6)

DOE's projects a cumulative installed base of about 15 GW of Integrated Gasification Fuel Cell (IGFC) plant by 2030 (DiPietro and Krulla 2010). Considering typical ramp-up profiles and initial commercial market introduction of IGFC systems in the 2020-2025 timeframe this implies an annual new SOFC capacity addition of 3-5 GW. To assess the implications of this level of market penetration as well as the longer-term impacts of SOFC production on demand for REEs, we consider three scenarios[13]:

1. ***Baseline Projection Gross Demand in 2030*** – the gross demand for new and replacement stacks based on the DOE's SOFC market penetration projections,
2. ***Baseline Projection Net Demand in 2030*** – taking into account a plausible mature recycling rate,
3. ***Long-Term Demand Potential*** – the demand that would result from SOFC stack replacement rate if all coal-fueled capacity were replaced with SOFC.

Scenario 1: Baseline Gross Demand for 2030

The DOE's current projections envision commercial introduction of SOFC around 2015 for initial applications (distributed generation, APUs, industrial, and military applications) and around 2020 for utility –scale applications. Because of their modest cost and high efficiency, as well as the potential to provide CO2 capture at marginal additional cost and loss of efficiency, SOFC sales are thought to increase rapidly, reaching 15 -20 GW of installed capacity by 2030.

Based on this, 2030 demand for new capacity, as stated above, is implied to be around 4 GW/yr. 2030 is an estimated 5-10 yrs into commercialization cycle of coal-based SOFC applications (which represent the majority of projected demand). Hence the projected annual demand is

[13] While other applications may be commercially significant, their impact in terms of production volume, and hence REE use, is small compared with coal-based applications.

sensitive to the assumptions surrounding the commercialization (e.g. initial commercial availability, rate of market penetration).

By 2030 only stacks installed in the initial years of IGFC commercialization will have reached the first stack replacement cycle, so stack replacement would add only about 1 GW/yr or less. Because this figure would rise dramatically in 2031 – 2035, we assume instead that the replacement rate is equal to new capacity additions for this analysis, resulting in a gross demand for SOFC stacks of 8 GW/yr.

Figure 5 shows the projected gross baseline REE demand for SOFC applications obtained by combining the projected REE use (in g/kW from Figure 4) with the projected gross SOFC demand (in GW/yr).

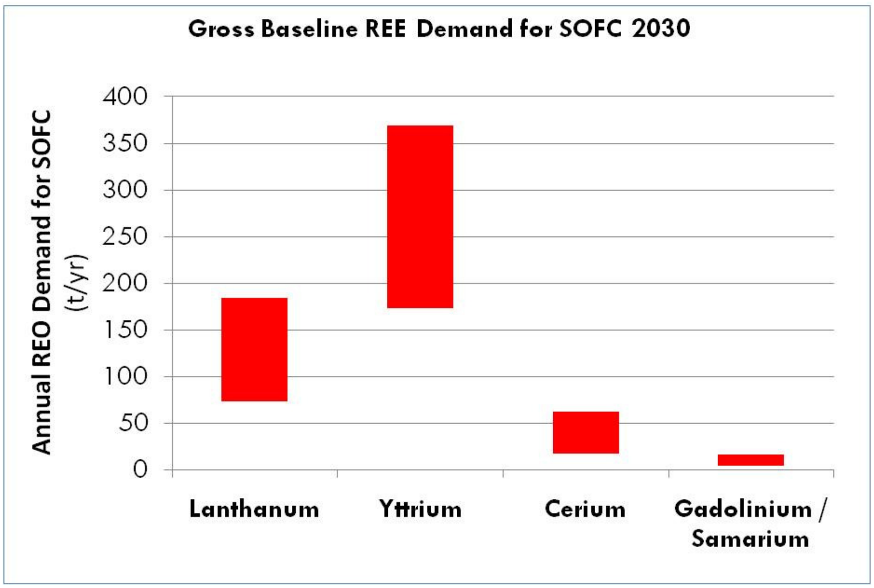


Figure 5 Projected Annual Gross REE Demand for New Systems and Replacement Stacks in 2030 (for Planar Anode-Supported SOFC, Demand in Metric Ton per Year Measured as Metals)

The combined demand for all REEs in this scenario would be 300 – 700 tons / yr. The range shown in the figure reflects only variations in REO use (compare Figure 4). Uncertainties in demand for both new and replacement SOFC capacity would further broaden that range. The reader is encouraged to consider all three scenarios to appreciate the impact of these uncertainties in demand.

The REE demand will of course depend on the choice and performance of SOFC technology. For example, if tubular cathode-supported SOFC technology were used, lanthanum demand would be about 16,000 – 20,000 t/yr, about 40-75x higher than for planar anode-supported technology (yttrium use would be comparable, no other REEs would be used).

Scenario 2: Baseline Net Demand for 2030 – The Impact of Recycling

Recycling of production waste as well as spent stacks will likely significantly reduce REE use for SOFC, especially in the long run. Given the concentration of rare earths and metals in used stacks, it is not unlikely that used stacks will be recycled. The processes used to process REE ores appear suitable for recycling of used stack materials.

Assuming the ceramics from the stacks are separated from the metals first, e.g. using conventional smelting technology, our analysis shows that the REO content of stack ceramics[14] would range from around 20% - 60%, depending on stack architecture, compared with 7-10% for typical ores(Haxel, Hedrick et al. 2002). Concentrations of REOs in production waste (e.g. overspray, rejected parts) can be even higher. These high concentrations will make recycling REEs from spent stacks attractive to REE producers.

Given the use patterns of SOFC, and the anticipated business structures for replacement stacks, a high rate of recycling would appear to be feasible. Especially if stack life remains relatively short (i.e. close to 5 yrs), it is likely that such a market for recycling REOs from the stack will arise even by 2030.

Given the attractiveness of recycling it would not likely impact the cost of SOFC strongly but it would be economically self-sufficient (i.e. REO producers would pay to recover portions of SOFC stacks).

Given the situation, a recycling rate of about 85% - 95% for production waste and spent stacks combined appears reasonable. With a 85% recycling rate the demand for REEs in 2030 would drop by around 50%, as shown in Figure 6. The resulting overall REE demand would be in the 160 – 360 t/yr range[15].

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[14] We exclude the nickel from the cermet anodes as we assume that in a recovery process that would be relatively straightforward and profitable to recover as nickel metal.

[15] Even by 2030 85% recycling will not lead to a 85% reduction in demand because a substantial portion of the market will still be a new market. With recycling, demand will stabilize sooner.

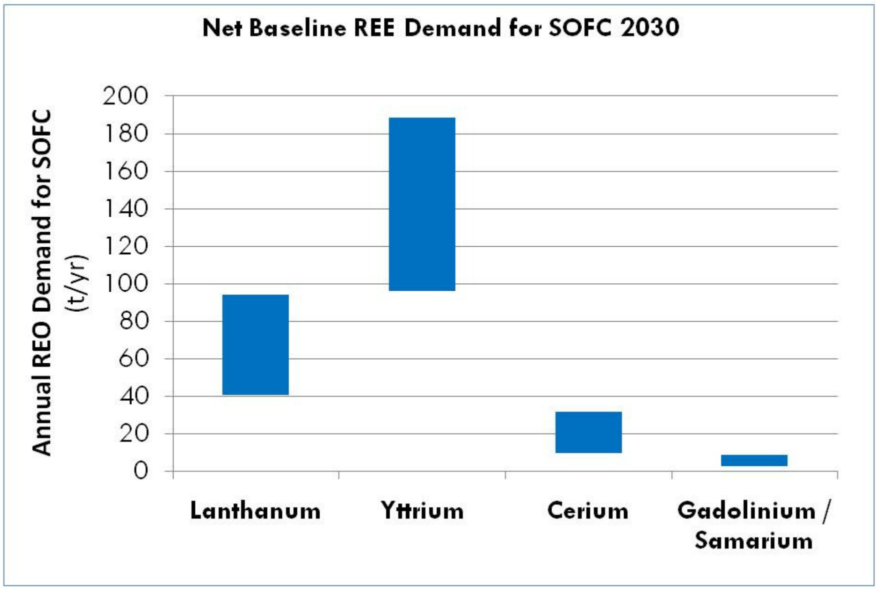

Figure 6 Projected Net REE Demand for SOFC in 2030 (for Planar Anode-Supported SOFC, Demand in Metric Ton per Year Measured as Metals)

Scenario 3: Long-Term REE Demand

Because 2030 is still early in the commercialization of SOFC technology, we thought it useful to assess the potential long-term contribution of SOFC to REE demand. To that end we considered a future scenario in which:

- Installed capacity of SOFC equals 100% of today's coal-fueled electric generating capacity. No growth in capacity is assumed, consistent with negligible net growth in coal-fired capacity over the past 10 yrs.
- SOFC stack life is 10 yrs, requiring stack replacement every 10 yrs.
- Recycling rates vary between 85 – 95%.
- REE use per kW is taken from the future range presented in Figure 4.

As can be seen in Figure 7, REE consumption under such a scenario is reduced by 30 – 80% compared with net baseline consumption. This indicates that REE use for SOFC is likely to be sustainable in the long-term.

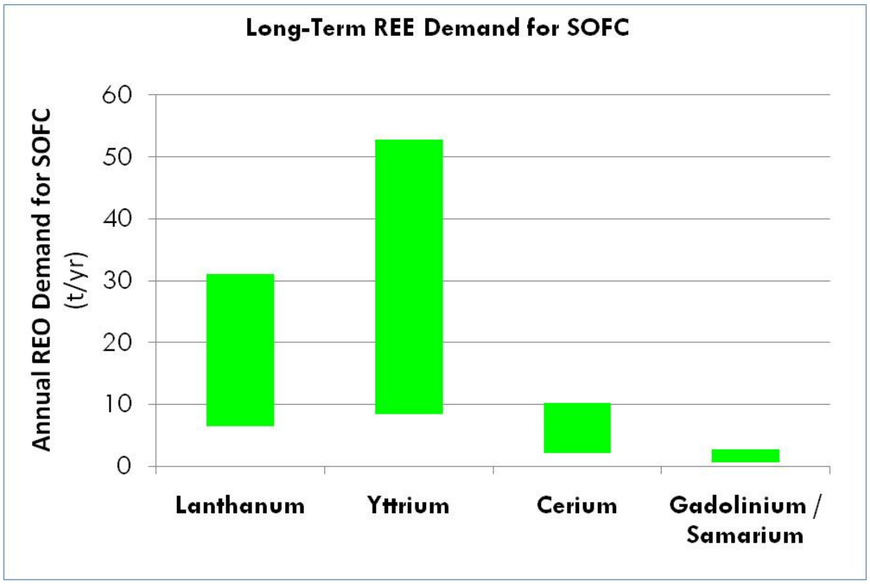

Figure 7 Projected Net Long-Term REE Demand for SOFC (for Planar Anode-Supported SOFC, Demand in Metric Ton per Year Measured as Metals)

Availability and Cost Impact (USDOE RFI Category 4)

Availability in Relation to SOFC Demand

The availability and prices for REOs have been the subject of much media attention recently. One reason for this interest is the recent dramatic rise in REO prices. The Economist reported that an index of REO prices has risen roughly fivefold since 2009 (Economist 2010), which is confirmed by a review of proprietary industry data (Metal-Pages 2010). The recent rise in REE prices is driven primarily by export restrictions being imposed by China. In recent years, China supplied around 90% of all REEs worldwide. Thus it is not surprising that China's announced 40% reduction of REE availability for export has led to dramatic price increases.

In addition to China, other countries, including the US, Australia, and Canada also hold considerable REE deposits. However, production from these countries has dwindled in recent years because Chinese suppliers were low-cost producers. Not surprisingly, in response to China's tightening of supplies, US, Australian, and Canadian companies are considering a resumption or increase in production of REEs in their respective countries.

Compared with the quantities used today, the additional potential REE demand from SOFC applications appears modest. Considering that SOFC demand will grow to projected levels over a period of 5-10 years, SOFC-driven demand for REE products appears unlikely to significantly challenge the supply chain or world reserves. In the following, production and reserve data for REEs are taken from a variety of USGS sources (Haxel, Hedrick et al. 2002; Salazar and McNutt 2010; USGS 2010):

- **Yttrium:**
  - The projected 2030 net baseline SOFC demand for yttrium is 96 ton/yr. A rationalization of yttrium use for the anode could reduce that figure to ~8 ton/yr, as represented in the future scenario.
  - Compared with a 2005 - 2009 US consumption rate fluctuating between 400 – 742 t/yr net baseline use for SOFC is significant. However, the figure for the future scenario is not likely to materially impact overall yttrium markets. USGS estimates world mine production to be at least 8,900 t/yr. In that context, even the impact of baseline demand would be modest. The impact of potential future SOFC demand on overall demand and prices of yttrium is likely to be small.
  - The abundance of yttrium in the earth's crust is 31 ppm similar to that of nickel and chromium. However, as other REEs, it is relatively disperse, with relatively few discovered more concentrated deposits (even in deposits yttrium is not very concentrated: 200 – 500 ppm typically). USGS estimates reserves of yttrium at 540,000 tons, about 220,000 of these in China, and about 100,000 tons in the US (mainly in the Mountain Pass deposit in California).
  - Virtually all Y used in the US is currently imported. More than 90% of world production is currently in China. The Chinese government has recently (in July) announced cuts in REE exports by about 40%.
  - Prices for bulk yttria (Y_2O_3, 99.9% pure or more, FOB China) have risen from around \$5/kg in 2002 to around \$40/kg in September 2010. High-volume prices for ultra-pure fine powders of yttria however can be 3-6 times higher than bulk prices, depending more on purity level and physical form.
- **Lanthanum:**
  - The projected 2030 net baseline SOFC demand for lanthanum oxide is 40-90t/yr.
  - Compared with annual global production of 33,000 t/yr, the potential demand for SOFC is modest and appears unlikely to materially alter lanthanum markets.
  - Lanthanum's abundance in the earth's crust is about 30 ppm, between that of tin and nickel, although, like other REOs, it is relatively disperse in the earth's crust. But compared with yttrium, REE deposits have high concentrations of lanthanum, with concentrations of ~25% in large deposits such as the Mountain Pass deposit in California and about 15% in many Chinese deposits. Given this, lanthanum reserves in producible deposits are thought to be over ten million tons.
  - Notwithstanding considerable US deposits, nearly 100% of lanthanum is currently imported in the US, mostly from China
  - The prices for bulk lanthanum oxide (La_2O_3, 99.9% pure or more, FOB China) have increased dramatically from around \$3/kg in 2002 to nearly \$50/kg in

September 2010. This dramatic price increase is driven partly due to short-term supply-demand imbalances caused by drastic increases in lanthanum use in NiMH batteries (primarily for hybrid vehicles) but strongly exacerbated by China's export restrictions.
    - If tubular cathode-supported SOFC are commercialized instead of planar anode-supported ones, lanthanum demand could be about 50x higher (about 60x higher content but likely longer stack life), or up to 7,000 t/yr. That level of demand would likely be sufficient to significantly affect lanthanum oxide markets and prices.
- **Cerium:**
    - Net demand for ceria for SOFC applications appears likely to remain below 10 t/yr.
    - Compared with US consumption of cerium compounds of around 2,000 t/yr this projected demand from SOFC is modest, and appears unlikely to materially affect overall Cerium markets and prices.
    - The abundance of cerium in the earth's crust, at about 60 ppm, is the most abundant of the lanthanides on earth. Its abundance is similar to that of chromium, though it is less concentrated. Found mostly in conjunction with the lanthanides, cerium-rich deposits are found predominantly in China, with smaller deposits in the US and Australia. Ceria are thought to represent almost half of REO reserves; i.e. about 50 million tons. Clearly, demand for SOFC will in not likely strain world reserves.
    - Prices for cerium too have risen sharply from about $2/kg in 2002 to around $37/kg in September 2010.
- **Gadolinium and Samarium:**
    - Projected 2030 baseline SOFC demand for gadolinium or samarium is 2-8 t/yr. Future demands could be reduced to below 1 t/yr.
    - Compared with report current global gadolinium production of around 400 t/yr this demand is modest. Samarium production is estimated at around 700 t/yr.
    - Gadolinium is about 5 times less abundant than yttria, at about 6 ppm, while samarium has a similar abundance as yttrium. Gadolinium and samarium reserves worldwide, found in China, the US, Australia, Brazil and India, are estimated to be around 1 million tons and 2 million tons respectively.
    - Gadolinium and samarium oxide prices were historically several times higher than those of yttria, lanthanum oxide, and ceria (about $10-$12/kg in 2002). Current (September 2010) prices are similar to the other rare earths of interest however at near $40-$50/kg.

The expectation is that if Chinese cuts persist for some time, and prices stabilize at this higher level, additional production capacity in other countries will supplant the reduced Chinese supply. However, because of the market risk the Chinese policy poses (China's marginal cost of production is still lowest, and hence could undercut other suppliers at any time if it wanted), such investments are likely to be made with caution.

Price Impact

The impact of REE prices on SOFC cost and economic viability in the context of IGFC systems(Kearns 2010) is limited, as REOs contribute around $10/kW to the first cost of SOFC:

- The total capital cost[16] + stack replacement cost together represent about 4.5 ¢/kWh
- Of the ~$1750/kW installed CAPEX of IGFC systems about $700/kW is related to the SOFC power unit;
- Of the $700/kW power unit, about $100/kW is the manufactured cost of the stack;
- Of the $175/kW stack, less than $10/kW are represented by the cost of the ceramic powders;.
- Of the ceramic powders, REEs represent about $10/kW based on September 2010 prices (based on pre-2008 prices, REOs would cost about $1/kW). The combined impact of $10/kW stack cost (including both capital cost effects and stack replacement cost) on LCOE would amount to around 0.05 ¢/kWh, which is in the margin of error of such LCOE estimates at this time.

Figure 8 provides a perspective on the historical impact of REE prices on SOFC stack cost.

Although further increases in REO cost are possible, long-term prices substantially above today's levels seem unlikely, because they would stimulate production in other countries (than China). So based on this analysis it appears unlikely that even the dramatic increases in the prices of REOs seen over the past years will not fundamentally alter the economics and viability of SOFC in central power applications.

It is worth noting that the price impact of REEs on SOFC based on some of the other cell architectures can be much more significant. For example, bulk REE cost contributes about $80/kW to the cost of tubular cathode-supported SOFC cells. Where REE use was hardly a factor in determining the relative cost competitiveness of various SOFC technologies based on 2002 prices, it appears that current prices lead to material differences in cost between various technologies.

[16] Total capital cost of the plant, not just the SOFC

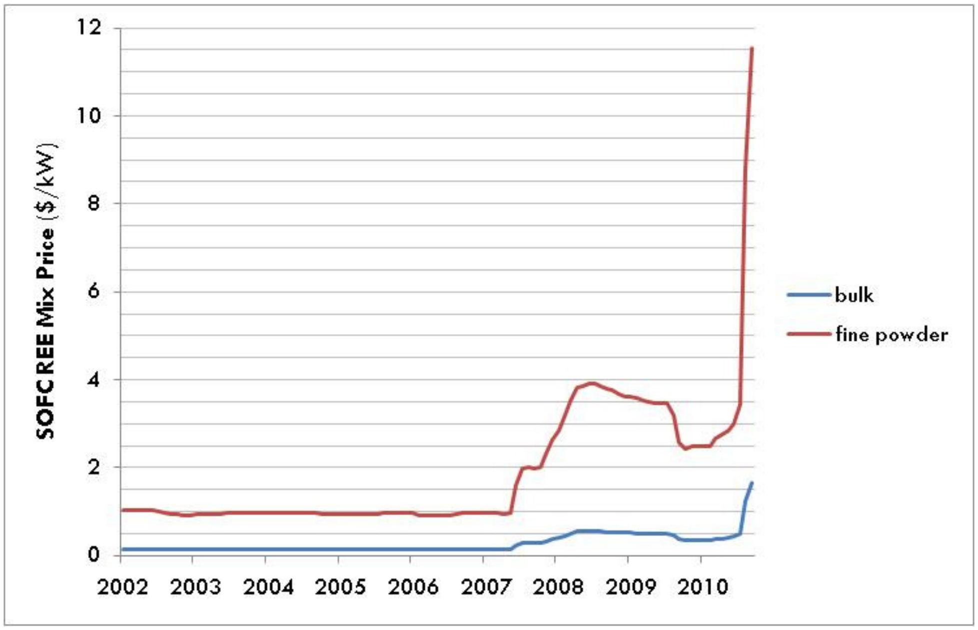

Figure 8 Historical Impact of REE Prices on SOFC Stack Cost (bulk figures represent just REE bulk prices FOB China, fine powder figures assume a 7x mark-up over bulk prices)[17]

Conclusion and Recommendations

A few REEs (notably yttrium, lanthanum, and cerium) are crucial to the functionality of SOFC; viable alternatives have not been identified for all REE applications in SOFC so far. However, it appears that this need not be of significant concern, given that demand for these REEs resulting from even highly successful commercialization of SOFC would not materially impact REE markets and because even dramatic further increases in REE prices would not likely alter the economics and viability of SOFC in central power applications decisively.

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[17] The mix price is determined by the sum of the products of REE use per kW (Figure 2) and REE prices for each of the REEs (all for state-of-the-art planar anode-supported SOFC). The fine powder mark-up presumably presents the supply-demand dynamics as well as processing cost. We show the 7x mark-up as a worst-case scenario.

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